

Hospital Factors Associated With Interhospital Transfer Destination for Stroke in the Northeast United States

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Background—We aimed to determine if there is an association between hospital quality and the likelihood of a given hospital being a preferred transfer destination for stroke patients.

Methods and Results—Data from Medicare claims identified acute ischemic stroke transferred between 394 northeast US hospitals from 2007 to 2011. Hospitals were categorized as transferring (n=136), retaining (n=241), or receiving (n=17) hospitals based on the proportion of acute ischemic stroke encounters transferred or received. We identified all 6409 potential dyads of sending and receiving hospitals, and categorized dyads as connected if ≥ 5 patients were transferred between the hospitals annually (n=82). We used logistic regression to identify hospital characteristics associated with establishing a connected dyad, exploring the effect of adjusting for different quality measures and outcomes. We also adjusted for driving distance between hospitals, receiving hospital stroke volume, and the number of hospitals in the receiving hospital referral region. The odds of establishing a transfer connection increased when rate of alteplase administration increased at the receiving hospital or decreased at the sending hospital, however this finding did not hold after applying a potential strategy to adjust for clustering. Receiving hospital performance on 90-day home time was not associated with likelihood of transfer connection.

Conclusions—Among northeast US hospitals, we found that differences in hospital quality, specifically higher levels of alteplase administration, may be associated with increased likelihood of being a transfer destination. Further research is needed to better understand acute ischemic stroke transfer patterns to optimize stroke transfer systems. (*J Am Heart Assoc.* 2020;9:e011575. DOI: 10.1161/JAHA.118.011575.)

Key Words: hospital quality • ischemic stroke • network analysis • patient transfer • systems of care

Patients with acute ischemic stroke (AIS) are frequently transferred between hospitals to access advanced expertise or resources,^{1–3} and interfacility transfer is becoming more common over time.^{3,4} This is likely because of

increased use of the drip-and-ship model,¹ as well as increasing evidence supporting endovascular thrombectomy for stroke.^{5–10}

Timeliness is critical during these interhospital transfers of AIS patients. Faster time to reperfusion is associated with improved clinical outcomes.^{11,12} While alteplase is frequently administered before transfer, endovascular thrombectomy cannot be performed until the patient arrives at an endovascular thrombectomy-capable hospital. Thus, development of efficient interhospital transfer processes is critical for effective stroke systems of care.¹³

Yet how decisions are made in the transfer of AIS patients is not well-described. In the transfer of patients with acute myocardial infarction, it has been shown that hospitals do not always choose the closest revascularization hospital with the best outcomes.¹⁴ In fact, an analysis of acute myocardial infarction transfers in Florida found that hospital relationships played a more important role in determining the transfer destination than distance or quality.¹⁵ Network analysis techniques may also be applied to understand and improve interhospital stroke transfer systems.¹⁶ As regional and

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Accompanying Table S1 and Figure S1 are available at <https://www.ahajournals.org/doi/suppl/10.1161/JAHA.118.011575>

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Clinical Perspective

What Is New?

- When hospitals in the northeast United States transfer stroke patients between hospitals, transfer connections are more likely to occur with higher-performing receiving hospitals.

What Are the Clinical Implications?

- Transfer relationships between hospitals tend to lead to stroke patients being transferred to higher-performing receiving hospitals, which may influence the quality of care received.

national bodies establish recommendations for interfacility transfer to ensure efficient stroke systems,^{17,18} it will be increasingly important to understand drivers of interhospital transfer decisions. A better understanding of hospital connections may contribute to modification and optimization of networks for the development of more efficient stroke systems of care.

To address this knowledge gap, we performed a hospital-level analysis on data including all Medicare beneficiaries with AIS who were transferred between northeast US hospitals during 2007 to 2011. We applied a network approach, focusing on connections between hospitals formed through stroke patient transfer. Our primary objective was to determine whether transfer connections between hospitals were more likely to form with higher quality receiving hospitals. Secondarily, we examined characteristics associated with receiving hospital status, and determined whether transfer connections were more likely to form with receiving hospitals with better patient outcomes. We hypothesized that higher quality hospitals would be more likely to be patient transfer destinations, but that because they attract a more complex case mix, receiving hospitals might not have significantly better unadjusted patient outcomes relative to non-receiving hospitals.

Methods

Data Source and Population

Our primary data source was the 2007 to 2011 Medicare enrollment, outpatient, and inpatient claims data for states in the northeast United States (Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont). This study was approved by the institutional review boards of Partners Healthcare and the Duke Clinical Research Institute; requirements for informed consent were

waived for the retrospective study. Because of data use agreements, we are unable to make available any data or analysis materials. We used discharge diagnosis *International Classification of Diseases, Ninth Revision, Clinical Modification (ICD-9-CM)* codes 433.x1, 434.x1, and 436 to identify patients hospitalized for acute ischemic stroke. We identified transferred patients as those with (1) an ED or inpatient billing claim from an initial hospital (transferring hospital), (2) an inpatient billing claim from a second hospital (receiving hospital) on the same or consecutive date, and (3) discharge from the second hospital.^{14,19} To focus on acute care transfers rather than those occurring because of downstream complications of care, we limited our analysis to those transfers occurring between hospital day 0 to 4, which included most stroke patient transfers (>70%, Figure S1).

As a secondary data source, we used data from the GWTG (Get With The Guidelines)-Stroke registry to determine hospital performance among hospitals participating in the registry. This registry is a voluntary, hospital-based quality improvement registry and collects a range of clinical data on patients hospitalized for stroke.²⁰ The GWTG-Stroke data were linked with the Medicare claims data using a unique combination of data fields (hospital identity code, admission and discharge dates, date of birth, and sex).²¹ These data included 64% of all hospitals in the region and 58% of all patients in the sample.

We also used data from the American Hospital Association 2008 database for hospital characteristics (ie, bed size, teaching status, rural/urban), and we used the Dartmouth Atlas to identify hospital referral regions.²² These data were available for all hospitals.

Variables of Interest

After identifying all stroke patient transfers, we categorized hospitals as transferring hospitals, retaining hospitals, and receiving hospitals based on previously used definitions.²³ Hospitals that received at least 15% of their annual ischemic stroke volume as patient transfers and that had at least 120 AIS discharges per year were categorized as receiving hospitals. Among the remaining hospitals we defined transferring hospitals as those that were not a receiving hospital, had at least 5 AIS discharges per year, and transfer out at least 15% of their ED and inpatient AIS volume. Retaining hospitals were the remainder (ie, did not transfer out $\geq 15\%$ of their annual AIS volume). Including the threshold of 120 discharges for the receiving hospital ensured that small-volume centers with a lower level of resources would not be included as a receiving hospital; and including the proportional threshold ensured that high-volume centers that do transfer some stroke patients for reasons other than available resources (eg, repatriation, enabling patients to be closer to

home, family, or local support) would not be identified as transferring hospitals.

For the purpose of identifying transfer connections between hospitals, we recognized that patient transfers would originate from hospitals that did not meet our definition of transferring hospital. After confirming that retaining hospitals were similar to transferring hospitals with respect to bed size and stroke patient volume, we combined retaining hospitals with transferring hospitals to create a single comparison group of potential sending hospitals. Therefore, we identified all potential sending hospitals as hospitals that were transferring hospitals or retaining hospitals.

Patient-level data were extracted both from the Medicare data (available for all patients) as well as the GWTG-Stroke registry (available for 54% of patients with Medicare inpatient claims). We obtained patient demographics and past medical history from the Medicare data. We used both Medicare data and the registry data to identify patients treated with alteplase. Stroke severity (based on National Institutes of Health Stroke Severity [NIHSS] score), onset-to-arrival time, and alteplase treatment times were extracted from the registry. For transferred patients, NIHSS scores were attributed to the receiving hospital and alteplase treatment variables (receipt of alteplase and door-to-needle time for treatment) were attributed to the hospital where the treatment was administered. If administered before transfer, alteplase administration was attributed to the sending hospital, and if administered after transfer, it was attributed to the receiving hospital. For receiving hospitals, the alteplase rate denominator did not include patients who were treated before transfer. As a patient-centered outcome measure, we calculated 90-day home-time for all discharged AIS patients as the number of days spent free of institutionalization during the 90 days post-discharge.^{11,24–26}

We used the American Hospital Association 2008 database to determine hospital teaching status and urban versus rural location. Hospitals with endovascular capabilities were identified as those with at least 5 inpatient discharges that included at least 1 of the following thrombectomy procedure codes in the claims data: 397.4, 397.5, 397.6.²⁷ Stroke center certification was identified using state certification, Det Norske Veritas Healthcare certification, or Joint Commission certification based on publicly available data for registry-participating hospitals.²⁸ We identified hospitals' Performance Achievement Award status annually by the publicly available GWTG source. Among GWTG registry-participating hospitals we also determined a composite quality measure adherence score. This score was based on each hospital's performance on 7 stroke care performance measures: intravenous alteplase within 2 hours, early antithrombotics and deep vein thrombosis prophylaxis, and discharge prescription of antithrombotics, anticoagulation for atrial fibrillation, statin

medication, and smoking cessation counseling.²⁹ Each hospital's score was based on the proportion of care opportunities across all patients that were fulfilled.²⁹

Statistical Analysis

We used descriptive statistics to characterize hospitals by transferring, retaining, and receiving hospital status. Differences in characteristics were compared using Pearson Chi-square for categorical variables and Kruskal–Wallis tests for continuous variables. We used logistic regression to identify characteristics associated with hospital status as a receiving hospital, comparing receiving hospitals to all potential sending hospitals (ie, transferring and retaining hospitals). Variables included in the model were hospital composite quality measure performance above versus below the median, mean distance travelled by transferred patients, annual stroke volume, and endovascular capability.

To identify factors associated with a receiving hospital being chosen as a patient transfer destination by potential sending hospitals, we identified all possible sending-to-receiving hospital dyads. A dyad is a given pair of hospitals, whether connected or not. Each hospital was part of many dyads, as we identified all potential pairs of connected sending and receiving hospitals. We coded each dyad as connected or not connected by patient transfer. We identified a connection if an average of ≥ 5 AIS patients per year were transferred from the potential sending hospital to the receiving hospital. We chose a threshold of 5 patients per year to avoid detecting inconsequential connections between hospitals. It was possible (and plausible) that sending and receiving hospitals could be part of >1 connected dyad, depending on the number of hospital transfer relationships that it had. We then performed multivariable logistic regression at the hospital dyad level, examining for characteristics associated with the presence of a connection between each sending-to-receiving hospital dyad. The binary outcome for the logistic regression model was therefore any connected dyad pairing versus all other unconnected hospital dyads defined on the basis that they were not partnering with other hospitals in transferring stroke cases. The variables included in the model were hospital performance of the potential sending hospital and the receiving hospital, driving distance between hospitals, annual stroke volume of the receiving hospital, and number of hospitals in the receiving hospital referral regions. We examined 3 alternative specifications of the model, using 3 different measures of hospital performance. The primary model was performed using all cases in the Medicare claims file and examined the proportion of eligible patients treated with alteplase. The secondary models examining composite quality measure performance score (as a proportion of available care opportunities fulfilled) and

hospital median door-to-needle time only included patients presenting to hospitals participating in the GWTG-Stroke registry. To test the robustness of our findings to our definition of sending-receiving connection, we also examined versions of each model in which the dyad-level outcome was a continuous measure of the number of patients transferred between a given pair of hospitals, rather than the binary measure of connected versus not. Because of the skewed distribution of the outcome, Poisson regression with log-link was used in these models. Given the sparseness of the data and lack of an established approach to adjust for clustering in a dyadic-based analysis like this one, our primary analyses did not include any adjustment for clustering. However, as a form of sensitivity analysis, we repeated our analysis adjusting for clustering by receiving hospital to evaluate the robustness of our findings, mimicking the idea of hierarchical models (used in scenarios where patients are nested within hospitals).

Finally, we examined patient outcomes using 90-day home-time. Given that post-discharge modified Rankin score is not available in administrative data, we used 90-day home-time, which has been previously demonstrated to be a patient-centered outcome, meaningful to stroke patients, and is readily available from administrative data.^{25,30} We first examined the variable at the patient-level, using a 2-level negative binomial regression model, including a random effect for hospital. We adjusted for patient-level factors of age, race, ethnicity, sex, NIHSS, previous stroke or transient ischemic attack (TIA), coronary artery disease or prior myocardial infarction, carotid stenosis, peripheral vascular disease, hypertension, hyperlipidemia, diabetes mellitus, and current smoking status. We also included an interaction for age and

NIHSS. We examined stepwise multi-level logistic regression models, first with only a random intercept for hospital, next adding patient-level factors, and finally, adding hospital-level factors (teaching status, rural location, median hospital NIHSS, mean annual stroke volume, stroke center status, and endovascular capability). We examined the incremental proportional change in variance with each model. Next, we performed logistic regression at the hospital dyad level, to determine whether either transferring or receiving hospital performance on 90-day home-time was associated with the presence of a connection between each sending-to-receiving hospital dyad. The variables included in the model were median hospital 90-day home-time of the potential sending and receiving hospitals, driving distance between hospitals, annual stroke volume of the receiving hospital, and number of hospitals in the receiving hospital referral regions.

All analyses were performed using SAS 9.4 (SAS Institute, Cary, NC).

Results

Characteristics of Northeast Hospitals

Of the 394 hospitals in the northeast during our study period, 17 hospitals were defined as receiving hospitals, receiving at least 15% of their annual AIS volume as patient transfers and having at least 120 AIS discharges per year. There were 136 transferring hospitals, transferring at least 15% of their annual ED and inpatient AIS volume, and there were 241 retaining hospitals, transferring at least 15% of their annual ED and inpatient AIS volume, and there were 241 retaining hospitals that were neither transferring nor receiving hospitals (Figures 1 and 2).

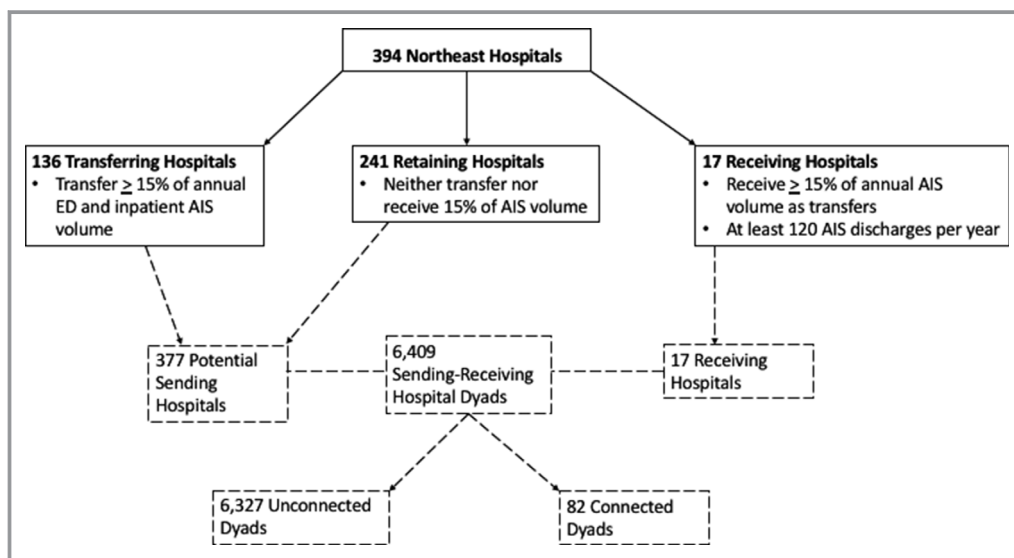


Figure 1. Logic model of hospital definitions. AIS indicates acute ischemic stroke; ED, emergency department.

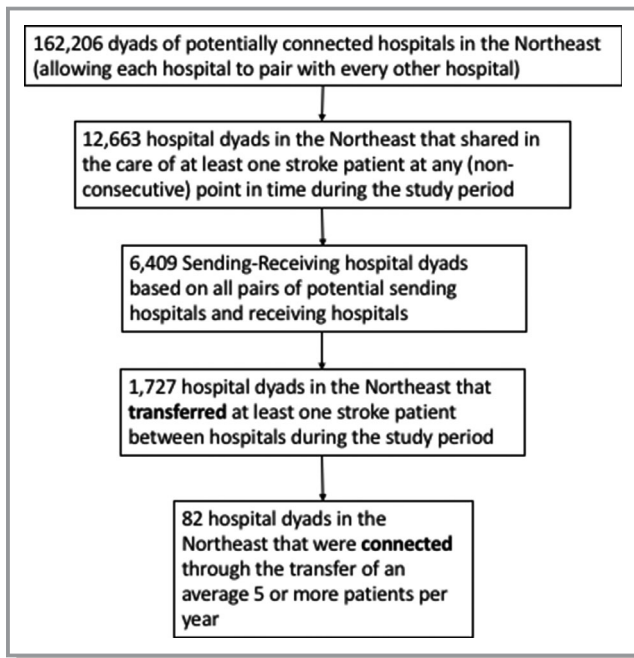


Figure 2. Flowchart of hospital dyads.

There were significant differences between the hospitals groups (Table 1). Receiving hospitals were typical referral hospitals in that they were most often academic (transferring hospitals 19%, retaining hospitals 56%, receiving hospitals 100%, $P<0.001$), were least often rural (transferring hospitals 54%, retaining hospitals 7%, receiving hospitals 6%, $P<0.001$), and had the highest participation in the GWTC registry (transferring hospitals 35%, retaining hospitals 76%, receiving hospitals 94%, $P<0.001$). Receiving hospitals also had the largest bed size and highest stroke volume (Table 1). Receiving hospitals were also most likely to have endovascular capabilities during the study period (transferring hospitals 0%, retaining hospitals 4%, receiving hospitals 9%, $P<0.001$) and to be ranked in the top 50 US hospitals by US News and World Report for Adult Neurology and Neurosurgery (25% of receiving hospitals versus 2% of non-receiving hospitals, $P<0.001$). In logistic regression modeling, longer travel distance for transferred patients, greater annual stroke volume, and endovascular capability were independently associated with receiving hospital status (Table S1).

Stroke Treatment Characteristics by Hospital Group

Across the groups of transferring, retaining, and receiving hospitals, both stroke severity and likelihood of alteplase treatment increased (group mean of hospital-level median NIHSS available for GWTC hospitals: transferring hospitals 6.5, retaining hospitals 8.2, receiving hospitals 8.9, $P<0.001$; alteplase rate available for all hospitals: transferring hospitals

36%, retaining hospitals 80%, receiving hospitals 85%, $P<0.001$), but there was no difference in hospital performance on door-to-needle time by hospital type among GWTC hospitals. Among GWTC-participating hospitals, receiving hospitals were most likely to receive the highest level of American Heart Association performance achievement award, an indicator of quality of care delivered (transferring hospitals 27%, retaining hospitals 40%, receiving hospitals 75%, $P=0.02$) and were more likely to be in higher quartiles on comprehensive quality measure performance (Table 1).

Relationship Between Hospital Performance and the Existence of a Connection Between Transferring and Receiving Hospitals

By allowing each hospital in the northeast to pair with any other hospital in the region, we identified 162 206 hospital dyads. Of these, 12 663 dyads shared in the care of at least 1 stroke patient at any point during the study period. When we limited to all hospital dyads between sending and receiving hospitals, we identified 6409 dyads. Of these, 1727 dyads transferred at least 1 stroke patient between hospitals during the study period, and 82 dyads were identified as connected through the transfer of an average of ≥ 5 patients during the study period.

Next, we performed logistic regression at the dyad level to identify factors associated with connected sending-receiving hospital dyads. A given receiving hospital had increased likelihood of receiving patients in transfer from a potential sending as its alteplase treatment rate increased (Table 2), and as its composite quality measure performance score increased (Table 3). Likelihood of a sending-receiving hospital connection was not associated with door-to-needle time for alteplase delivery at the receiving hospital (Table 4). These findings held when accounting for sending hospital performance, driving distance, stroke volume, and number of hospital options. These findings also held when we used a continuous measure of hospital connection based on the number of patients transferred between hospitals. In the sensitivity analysis where we attempted to account for the clustering effect of the receiving hospitals, odds ratios remained stable but were no longer statistically significant (Table 5).

Relationship Between Hospital Outcomes and the Existence of a Connection Between Transferring and Receiving Hospitals

Median 90-day home-time was used to examine patient outcomes following discharge. Much of the variation in patients' 90-day home-time was attributable to patient-level factors (47% to patient-level factors, and 19% to hospital-level factors). Unadjusted and adjusted median hospital-level 90-day

Table 1. Hospital Characteristics

Variable	Level	Overall (N=394)	Transferring Hospitals (n=136) n (%)	Retaining Hospitals (n=241) n (%)	Receiving Hospitals (n=17) n (%)	P Value
Hospital characteristics						
GWTC fully participating hospital		248 (62.94)	48 (35.29)	184 (76.35)	16 (94.12)	<0.0001
Academic/teaching hospital		178 (45.64)	26 (19.40)	135 (56.49)	17 (100.00)	<0.0001
Rural location		90 (23.08)	72 (53.73)	17 (7.11)	1 (5.88)	<0.0001
Hospital size— number of beds	500+	50 (12.82)	3 (2.24)	34 (14.23)	13 (76.47)	<0.0001
	400 to 499	27 (6.92)	1 (0.75)	25 (10.46)	1 (5.88)	
	300 to 399	53 (13.59)	6 (4.48)	45 (18.83)	2 (11.76)	
	200 to 299	72 (18.46)	17 (12.69)	55 (23.01)	0 (0.00)	
	100 to 199	93 (23.85)	37 (27.61)	55 (23.01)	1 (5.88)	
	50 to 99	45 (11.54)	29 (21.64)	16 (6.69)	0 (0.00)	
	25 to 49	39 (10.00)	33 (24.63)	6 (2.51)	0 (0.00)	
	6 to 24	11 (2.82)	8 (5.97)	3 (1.26)	0 (0.00)	
Stroke center type	State	154 (69.37)	37 (92.50)	111 (66.87)	6 (37.50)	0.003
	DNV	3 (1.35)	0 (0.00)	3 (1.81)	0 (0.00)	
	TJC	54 (24.32)	2 (5.00)	43 (25.90)	9 (56.25)	
	No Certification	11 (4.95)	1 (2.50)	9 (5.42)	1 (6.25)	
	Missing	26 (10.48)	8 (16.67)	18 (9.78)	0 (0.00)	
Number of AIS admissions 2007–2011	Median	297	109	387	946	<0.0001
	25th	129	65	233	850	
	75th	538	214	626	1401	
Endovascular capabilities		19 (4.82)	0 (0.00)	9 (3.73)	10 (58.82)	<0.0001
Mean DTN Time [†]	Median	218 (81.99)	29 (82.75)	173 (82.91)	16 (80.14)	0.19
	25th	74.52	79.29	74.87	71.13	
	75th	93.64	96.33	94.00	82.70	
Mean NIHSS [†]	Median	8.08	6.53	8.21	8.87	<0.0001
	25th	6.53	5.04	6.90	8.14	
	75th	9.33	8.21	9.37	9.50	
Intravenous alteplase rate (arrive by 2, treat by 3) [†]	Median	78.57	36.36	80.00	84.66	<0.0001
	25th	50.00	0.00	50.00	77.12	
	75th	92.31	80.00	94.12	90.98	
DTN within 60 min rate [†]	Median	25.00	20.00	25.00	30.37	0.24
	25th	12.00	0.00	12.50	21.18	
	75th	37.50	35.29	37.21	44.01	
AHA performance achievement award	Gold or Gold Plus and TS Honor Roll	76 (41.08)	7 (26.92)	57 (39.86)	12 (75.00)	0.02
	Gold or Gold Plus Without TS Honor Roll	82 (44.32)	12 (46.15)	67 (46.85)	3 (18.75)	
	All Others	27 (14.59)	7 (26.92)	19 (13.29)	1 (6.25)	
	Missing	63 (25.40)	22 (45.83)	41 (22.28)	0 (0.00)	

Continued

Table 1. Continued

Variable	Level	Overall (N=394)	Transferring Hospitals (n=136) n (%)	Retaining Hospitals (n=241) n (%)	Receiving Hospitals (n=17) n (%)	P Value
Achievement measure performance quartile	Highest	62 (25.00)	10 (20.83)	46 (25.00)	6 (37.50)	0.02
	High	62 (25.00)	7 (14.58)	47 (25.54)	8 (50.00)	
	Low	62 (25.00)	13 (27.08)	47 (25.54)	2 (12.50)	
	Lowest	62 (25.00)	18 (37.50)	44 (23.91)	0 (0.00)	

AHA indicates American Heart Association; AIS, acute ischemic stroke; DTN, door-to-needle; GWTG, Get With The Guidelines; NIHSS, National Institutes of Health Stroke Scale; TS, target stroke; TJC, The Joint Commission.

† indicates variables for which data were only available for GWTG-Stroke-participating hospitals.

home-time were similar between transferring, retaining, and receiving hospitals (unadjusted: transferring hospitals 54 days [interquartile range 47–63], retaining hospitals 50 days [interquartile range 36–58], receiving hospitals 52 days [interquartile range 42–60]; adjusted: transferring hospitals 43 [42.7–43.5], retaining hospitals 42.9 [42.5–43.4], receiving hospitals 43.5 [interquartile range 42.4–44.1]). When we performed logistic regression at the dyad level to determine whether hospital outcomes were associated with the existence of a sending-receiving hospital connection, we found that receiving hospital performance on 90-day home time was not associated with likelihood of patient transfer destination. This finding held when accounting for transferring hospital outcomes, driving distance, annual stroke volume, and number of hospital options (Table 6).

Discussion

To our knowledge, this is the first evaluation of hospital factors associated with transfer destinations among AIS patients transferred to another facility for ongoing acute care.

Table 2. Relationship Between Receiving Hospitals' Performance on Alteplase Delivery and Likelihood of a Sending-to-Receiving Hospital Transfer Connection in Multivariable Model

Variable	Odds Ratio	95% CI
Transferring hospital alteplase rate (per 10% increase)	0.73	0.66 to 0.81
Receiving hospital alteplase rate (per 10% increase)	1.47	1.07 to 2.02
Driving distance (per 20 miles increase)	0.66	0.51 to 0.87
Receiving hospital annual stroke volume (per 100 patient increase)	2.24	1.71 to 2.92
Number of hospitals in hospital referral region (per 10 hospital increase)	1.16	0.99 to 1.35

This logistic regression model identified all dyads of potential sending-to-receiving hospitals. We examined characteristics associated with dyads connected by patient transfer vs all other unconnected dyads.

Characterizing these patterns of hospital connections and the movement of stroke patients between hospitals is an important step toward the aim of developing efficient stroke systems of care and identifying opportunities for improvements in care. Among acute care hospitals in the northeast United States, we identified 17 receiving hospitals with annual stroke volume >120 Medicare-aged patients and at least 15% of that volume received through interhospital transfer. We found that presence and strength of connections between potential sending and receiving hospitals were potentially more likely to occur as the receiving hospital's alteplase treatment rate and quality measure score increased, however, these findings were no longer significant when we adjusted for clustering. Studies with larger numbers of receiving hospitals and larger numbers of hospitals connected with receiving hospitals will be needed to confirm our results with adequate power. Additionally, the likelihood of a transfer connection was not associated with receiving hospitals' median 90-day home-time post-discharge which has been previously identified as a patient-centered measure of outcome.

Table 3. Relationship Between Receiving Hospitals' Composite Quality Score and Likelihood of a Sending-to-Receiving Hospital Transfer Connection in Multivariable Model

Variable	Odds Ratio	95% CI
Transferring hospital composite score (per 1% increase)	0.96	0.93 to 0.99
Receiving hospital composite score (per 1% increase)	1.35	1.10 to 1.67
Driving distance (per 20 miles increase)	0.69	0.55 to 0.86
Receiving hospital annual stroke volume (per 100 patient increase)	2.15	1.73 to 2.69
Number of hospitals in hospital referral region (per 10 hospital increase)	1.18	1.03 to 1.35

This logistic regression model identified all dyads of potential sending-to-receiving hospitals. We examined characteristics associated with dyads connected by patient transfer vs all other unconnected dyads.

Table 4. Relationship Between Receiving Hospitals' Performance on Door-to-Needle Time for Alteplase and Likelihood of a Sending-to-Receiving Hospital Transfer Connection in Multivariable Model

Variable	Odds Ratio	95% CI
Transferring hospital median DTN time (per 10 min increase)	1.37	1.16 to 1.62
Receiving hospital median DTN time (per 10 min increase)	0.74	0.52 to 1.06
Driving distance (per 20 miles increase)	0.63	0.45 to 0.89
Receiving hospital annual stroke volume (per 100 patient increase)	2.11	1.56 to 2.87
Number of hospitals in hospital referral region (per 10 hospital increase)	1.02	0.84 to 1.25

This logistic regression model identified all dyads of potential sending-to-receiving hospitals. We examined characteristics associated with dyads connected by patient transfer vs all other unconnected dyads.

Transfer of stroke patients is becoming increasingly common.^{3,4} Transfers are typically for the purpose of moving patients to centers with higher levels of resources and greater expertise in stroke care delivery, however increasingly in recent years transfers may also occur to lower cost settings for appropriate lower acuity patients. Thus, it is potentially concerning that some receiving hospitals in the region were not above the median for composite quality measure performance. However, when we examined hospital characteristics associated with a transfer relationship between a sending and receiving hospital, we did find that as the receiving hospital's composite quality measure performance increased, the likelihood of a transfer connection between hospitals increased. This suggests that transfer relationships are still connecting sending hospitals to receiving hospitals of a relatively higher quality even when the receiving hospital is not in the highest absolute category.

We did not find that the likelihood of a sending-receiving transfer connection was associated with receiving hospitals' performance on the patient-centered outcome of 90-day home-time. This finding is not surprising, given that previous work has demonstrated that regionalized stroke care tends to concentrate patients with more severe strokes and post stroke complications at more advanced stroke centers.^{2,4} Two studies have found that transferred stroke patients tend to

have higher stroke severity,^{2,4} and within the Michigan Stroke Registry, transfer was associated with worse patient outcomes even after adjusting for stroke severity.⁴ Furthermore, our outcome of interest was 90-day home-time, or the number of days that patients spent free of institutionalization in the 90 days post-discharge from stroke hospitalization. Given that transferred patients have been found to be more frequently discharged to inpatient rehab,² it is not surprising that 90-day home-time was not better at receiving hospitals, and that it was not associated with likelihood of a transfer connection.

The topology of hospital connections in the stroke system of care has not been well-described previously. This regional analysis provides a valuable foundation for further work to better understand and improve the structure of interhospital connections. Future studies should evaluate for regional differences in transfer patterns, as well as how these interhospital transfer relationships are changing in the endovascular era. Better understanding transfer relationships between hospitals and the structural nature of hospital relationships will be critical for improving and optimizing stroke systems of care.

Applications of network analysis have enabled us to gain new insights into transfer patterns and interhospital

Table 5. Relationship Between Receiving Hospitals' Performance on Alteplase Delivery and Likelihood of a Sending-to-Receiving Hospital Transfer Connection in Multivariable Model, With and Without Adjustment for Clustering

Variable	Original Output			Adjusted for Clustering		
	OR	Lower Limit of 95% CI	Upper Limit of 95% CI	OR	Lower Limit of 95% CI	Upper Limit of 95% CI
Transferring hospital alteplase rate (per 10% increase)	0.73	0.656	0.811	0.69	0.607	0.776
Receiving hospital alteplase rate (per 10% increase)	1.47	1.066	2.018	1.41	0.855	2.342
Drive distance (per 20 miles increase)	0.66	0.505	0.866	0.53	0.376	0.740
RH annual stroke volume (per 100 increase)	2.24	1.714	2.915	1.15	0.683	1.942
RH HRR-level number of hospitals (per 10 increase)	1.16	0.993	1.353	0.94	0.709	1.252

Intraclass correlation coefficient (ICC) for the model adjusted for clustering is 20% or 0.20. HRR indicates hospital referral region; RH, receiving hospital.

Table 6. Relationship Between Receiving Hospitals' Patient Outcomes (90-Day Home-Time) and Likelihood of a Sending-to-Receiving Hospital Transfer Connection in Multivariable Model

Variable	Odds Ratio	95% CI
Transferring hospital median 90-d home time (per 10 d increase)	1.38	1.11 to 1.73
Receiving hospital median 90-d home time (per 10 d increase)	0.84	0.69 to 1.03
Driving distance (per 20 miles increase)	0.65	0.52 to 0.82
Receiving hospital annual stroke volume (per 100 patient increase)	2.46	1.99 to 3.04
Number of hospitals in hospital referral region (per 10 hospital increase)	1.19	1.07 to 1.33

This logistic regression model identified all dyads of potential sending-to-receiving hospitals. We examined characteristics associated with dyads connected by patient transfer vs all other unconnected dyads.

relationships that may influence care outcomes and that are amenable to modification. By focusing on hospital relationships, this approach encourages an understanding of hospitals within the network in which they sit, and an understanding of the network as a whole. We began this work in the northeast because the high penetration of the GWTC-Stroke registry enables inclusion of more detailed hospital-level performance data. However, as we have now begun to demonstrate the value of this analytic approach, this work sets the stage for a national study to understand the movement of patients through systems of care and the impact of network-level effects on patient care.

This work does have potential limitations. First, the regional nature of the analysis may limit generalizability, as transfer patterns and decisions may be influenced by local and regional factors and may be different in other regions of the United States. Secondly, these data pre-date the endovascular era and therefore more recent data might show different patterns of care emerging. Despite using 2007 to 2011 data, we believe that these findings are useful to provide a baseline understanding of stroke transfer relationships and validate these new analytic approaches. This method also allows for the inclusion of new data as they become available, and this will enable better understanding of how the stroke system evolves over time and with changes in evidence and best practices. Additionally, the definitions that we used for categorizing hospitals as transferring, retaining, and receiving hospitals have not been previously used because we did not have any similar work to reference in their development. However, we believe that the definitions have face validity, and reviewing characteristics of the categorized hospitals reaffirmed this. In addition, our primary analytic approach did not adjust for clustering, so the estimates are likely overly optimistic. However, there is not an agreed upon approach to adjust for clustering in this scenario and our approach is consistent with that taken in other analyses of sparse network data.³¹ Nevertheless, this analysis should be repeated in larger data sets adequately sized (within and across “clusters”) to maintain appropriate power with cluster-adjustment.

Finally, there are likely other factors that influence patient transfer destination, including hospital ownership and affiliation, existence of telestroke relationships between hospitals, and also more dynamic factors such as availability of different modes of patient transport. Unfortunately, we did not have these data to incorporate into our analysis.

Conclusions

Among northeast US hospitals, we found that connections between transferring and receiving hospitals may be more likely to exist with higher-performing receiving hospitals. Further research is needed to better understand AIS transfer patterns to optimize patient outcomes within a stroke system of care.

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Disclosures

Dr Hernandez reports research relationships with BMP, GlaxoSmithKline, Janssen, Daiichi, Novartis, and Genentech, and reports consulting relationships with Bayer and Novartis. Dr Schwamm is the principal investigator of investigator-initiated study of extended-window intravenous thrombolysis funded by the National Institutes of Neurological Disorders and Stroke (ClinicalTrials.gov/show/NCT01282242) and Genentech provides alteplase free of charge to Massachusetts General Hospital as well as supplemental per-patient payments to participating sites for this trial. Dr Schwamm also reports serving as stroke systems consultant to the Massachusetts Department of Public Health, serving as scientific consultant on trial design and conduct to Penumbra (data and safety monitoring committee, Separator 3D and MIND trial), serving as a scientific consultant on trial design

and conduct to Medtronic (Victory AF and Stroke AF trials), and serving as a scientific consultant on trial design and conduct to Genentech (steering committee, TIMELESS trial). Dr Goldstein has had consulting relationships with CSL Behring and Octapharma, and clinical research supported by Portola and Pfizer. The remaining authors have no disclosures to report.

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SUPPLEMENTAL MATERIAL

Table S1. Characteristics Associated with Receiving Hospital Status in Multivariable Logistic Regression Model.

Variable	Odds Ratio	95% Confidence Interval
Composite quality measure performance above vs below median	1.58	0.40 - 7.03
Mean distance travelled by transferred patients (per 20 miles increase)	1.03	1.02 - 1.05
Annual stroke volume (per 100 increase)	6.43	2.17 - 24.08
Endovascular capabilities	9.11	1.81 – 54.44

This logistic regression model compared receiving hospitals to all potential sending hospitals (i.e., transferring and retaining hospitals) in order to identify characteristics associated with receiving hospital status.

Figure S1. Histogram of Stroke Transfers by Hospital Day.

